

---

## EXECUTIVE SUMMARY

### S.1 BACKGROUND

Title IV of the Clean Air Act Amendments of 1990 calls for a 10 million ton reduction in annual emissions of sulfur dioxide (SO<sub>2</sub>) in the United States by the year 2010, which represents an approximately 40 percent reduction in anthropogenic emissions from 1980 levels. Implementation of Title IV is referred to as the Acid Rain Program; the primary motivation for this section of the Clean Air Act Amendments is to reduce acid precipitation and dry deposition.<sup>1</sup> This assessment has been prepared at the request of the U.S. Environmental Protection Agency (U.S. EPA), Acid Rain Division, to quantify the expected human health benefits associated with the SO<sub>2</sub> emissions reductions required under the Acid Rain Program. This assessment is intended to contribute to assessments of costs and benefits of the Clean air Act, such as the studies called for under Sections 812 and 901 of the 1990 Amendments. The Act requests that benefits and costs be quantified to the extent possible given available scientific and economic information. This report, therefore, focuses on quantification of potential health benefits of Title IV in both numbers of specific health effects expected to be reduced and their monetary valuation.

This report provides estimates of the human health benefits expected to result from changes in ambient sulfate aerosol concentrations in the eastern United States. Title IV requirements are expected to result in significant reductions in SO<sub>2</sub> emissions in the eastern United States.<sup>2</sup> This will mean lower gaseous SO<sub>2</sub> concentrations close to major emissions sources, lower sulfate aerosol concentrations (including acid and nonacid aerosols) throughout the region, and lower acid precipitation throughout the region. This report focuses on ambient sulfate aerosols because the potential human health benefits of this pollutant reduction have not been fully quantified in previous analyses, because the potential human health benefits are substantial, and because a quantitative assessment is feasible for sulfate aerosols, given available scientific and economic information. This report does not attempt to quantify various other possible human health benefits of Title IV, such as those that might result from nitrogen oxide reductions and “piggy back” toxics or particulate reductions.

---

<sup>1</sup> Throughout this report the terms “acid rain” and “acid precipitation” include dry deposition.

<sup>2</sup> SO<sub>2</sub> emissions are also controlled under Title I of the Clean Air Act.

## S.2 METHODS

Sulfate aerosols are a substantial share of total ambient fine particulate matter in the eastern United States. A large body of epidemiology literature examines the relationship between ambient particulate matter and health effects. Some of these studies have specifically examined sulfate aerosols, and many have examined more broad measures of particulate matter such as  $PM_{2.5}$  (particulate matter with aerodynamic diameter of 2.5 microns or less) or  $PM_{10}$  (particulate matter with aerodynamic diameter of 10 microns or less). Scientific debate and uncertainty continue concerning the extent to which sulfates may or may not be the key causative constituent of this observed association between health effects and particulate matter. Sulfate aerosols, and especially that portion of sulfate aerosols that is acidic, continue to be considered one of the likely causative agents in the observed association between particulate matter and health effects in the eastern United States. In this assessment, the available epidemiology evidence is applied on the presumption that sulfate aerosols are at least a contributing causative constituent of  $PM_{2.5}$ . This assessment does not assume that sulfate aerosols are the only causative constituent of  $PM_{2.5}$ .

This assessment also relies on available economic information for estimates of willingness to pay (WTP) for changes in risks of specific health effects. Economic values for changes in risks of human health effects should reflect the full costs to the affected individual and to society. The full costs of an adverse health effect include financial losses such as medical expenses and lost income (referred to as the cost of illness), plus less tangible costs such as pain and discomfort, restrictions on nonwork activities, and inconvenience to others. WTP, as a monetary measure for a change in health risk, is defined as the dollar amount that would cause the affected individual to be indifferent to experiencing an increase in the risk of the health effect or losing income equal to that dollar amount. WTP measures of monetary value for changes in health risks thus exceed health care and other out-of-pocket costs that are associated with illness or premature death, because WTP reflects these as well as other less tangible effects of illness or premature death on a person's quality of life.

Table S-1 lists the five major quantification steps in this assessment and gives a brief explanation of the quantification method selected for each step. Other related assessments are ongoing at the U.S. EPA, such as the Section 812 studies concerning the costs and benefits of the Clean Air Act Amendments as a whole and the review of the National Ambient Air Quality Standards (NAAQS) for particulate matter. Although there are many similarities in the general approaches being taken in the health benefits components of these other assessments and in this assessment for Title IV, many of the details of the assessment methods may differ. Many of these differences stem from the fact that this assessment focuses on  $SO_2$  emissions and sulfate aerosols only, while the NAAQS assessment considers all sources of ambient particulate matter and the Section 812 studies consider not only all sources of ambient particulate matter but all air pollutants regulated under the Clean Air Act.

**Table S-1**  
**Quantification Steps for this Assessment of**  
**Health Benefits Due to Sulfate Aerosol Reductions**

Quantification Steps	Selected Quantification Method
1. Changes in SO <sub>2</sub> emissions in the United States	Use ICF Resources (1994) estimates for the United States of 1985 emissions, 1997 emissions with Title IV, and 2010 emissions with and without Title IV (prepared for EPA)
2. Changes in atmospheric sulfate aerosol concentrations in the eastern United States and eastern Canada	Use EPA's Regional Acid Deposition Model (RADM) runs for each of the SO <sub>2</sub> emissions scenarios
3. Numbers of people residing at each location where atmospheric sulfate concentrations change in the eastern United States and Canada	Match the RADM 80 km × 80 km grid to population data using a Geographic Information System; population based on 1990 Census data for block groups (Chapter 3)
4. Changes in sulfate-related health effects: changes in numbers of cases of each type of health effect	Use concentration-response functions derived from selected epidemiology studies on health effects of sulfates or PM <sub>2.5</sub> (Chapter 4)
5. Monetary valuation of changes in health	Use selected willingness-to-pay estimates from the available economics literature for changes in health risks or health effects (Chapter 5)

### S.3 RESULTS

Table S-2 summarizes the estimates of annual human health benefits for the sulfate aerosol reductions attributed to Title IV in 1997 and 2010 for the 31-state eastern United States area. Table S-3 gives the results for Ontario and Quebec. These estimates are based on the default quantification assumptions, some of which are changed in the sensitivity analyses discussed below. The mean total annual estimated health benefit (in 1994 U.S. dollars) for 1997 in the United States is \$10.6 billion, and rises to \$40.0 billion by the year 2010, when Title IV requirements are expected to be fully implemented.

The health benefit estimates are dominated by premature mortality and chronic bronchitis. The numbers of cases in these health effects categories are relatively small, but the high monetary values per case result in large monetary benefits for these categories. Premature mortality reductions account for about 88 percent of the total health benefits. Chronic bronchitis reductions

**Table S-2**  
**Estimates of Annual Human Health Benefits of Title IV**  
**for the Eastern United States with Default Assumptions**  
**(millions of 1994 dollars)**

Health Effect	1997						2010					
	Annual Number of Cases Prevented			Annual Monetary Value			Annual Number of Cases Prevented			Annual Monetary Value		
	20th Percentile	Mean	80th Percentile	20th Percentile	Mean	80th Percentile	20th Percentile	Mean	80th Percentile	20th Percentile	Mean	80th Percentile
Premature Mortality	408	2,568	5,714	\$1,428.0	\$9,307.2	\$19,999.0	1,539	9,678	21,544	\$5,386.5	\$35,234.8	\$75,404.0
Chronic Bronchitis (new cases)	1,648	3,864	6,590	\$507.5	\$974.0	\$1,377.5	6,179	14,564	24,715	\$1,903.0	\$3,705.8	\$5,165.3
Respiratory Hospital Admissions	663	805	918	\$5.7	\$11.3	\$17.1	2,501	3,036	3,462	\$21.5	\$42.4	\$64.6
Cardiac Hospital Admissions	510	673	867	\$4.6	\$9.4	\$13.9	1,924	2,552	3,270	\$17.5	\$35.7	\$52.5
Asthma Symptom Days	791,232	1,604,341	2,373,697	\$20.9	\$56.9	\$93.2	2,983,490	5,951,693	8,950,470	\$78.7	\$212.9	\$351.3
Restricted Activity Days (net)	1,202,785	2,467,066	3,809,253	\$70.6	\$147.0	\$228.6	4,514,939	9,283,999	14,298,930	\$265.0	\$554.7	\$857.9
Days with Lower Respiratory Symptoms (net)	2,028,424	5,002,393	7,259,946	\$31.8	\$56.7	\$90.0	7,614,168	18,619,000	27,251,920	\$119.3	\$212.8	\$338.0
Total Annual Health Benefits				\$3,219.1	\$10,562.3	\$20,684.1				\$12,131.5	\$39,999.0	\$77,915.5

**Table S-3**  
**Estimates of Annual Human Health Benefits of Title IV**  
**for Ontario and Quebec, Canada with Default Assumptions**  
**(millions of 1994 dollars)**

Health Effect	1997				2010			
	Annual Number of Cases Prevented				Annual Number of Cases Prevented			
	20th Percentile	Mean	80th Percentile	Annual Monetary Value	20th Percentile	Mean	80th Percentile	Annual Monetary Value
Premature Mortality	35	217	483	\$122.5 \$801.2 \$1,690.5	37	232	517	\$129.5 \$839.2 \$1,809.5
Chronic Bronchitis (new cases)	140	329	562	\$43.3 \$83.3 \$117.4	150	355	601	\$46.3 \$91.0 \$125.8
Respiratory Hospital Admissions	56	68	78	\$0.5 \$0.9 \$1.4	60	73	83	\$0.5 \$1.0 \$1.6
Cardiac Hospital Admissions	43	57	73	\$0.4 \$0.8 \$1.2	46	61	78	\$0.4 \$0.9 \$1.3
Asthma Symptom Days	66,915	133,825	200,746	\$1.8 \$4.8 \$7.9	71,594	142,267	214,783	\$1.9 \$5.1 \$8.4
Restricted Activity Days (net)	97,734	199,194	309,526	\$5.7 \$12.0 \$18.6	104,568	215,270	331,168	\$6.1 \$13.0 \$19.9
Days with Lower Respiratory Symptoms (net)	164,822	401,231	589,916	\$2.6 \$4.5 \$7.3	176,347	433,821	631,165	\$2.8 \$4.9 \$7.8
Total Annual Health Benefits				\$273.3 \$907.6 \$1,746.9				\$290.8 \$955.0 \$1,868.1

are an additional 9 percent of the total. Together they represent about 97 percent of the total estimated health benefits.

The largest numbers of cases reduced are for asthma symptom days, restricted activity days, and days with acute lower respiratory symptoms. The restricted activity days are net of days in the hospital and asthma symptom days because these health effects categories may substantially overlap. The lower respiratory symptom days are net of the fraction of restricted activity days that might also be attributed to lower respiratory symptoms. In 2010, the estimated reduction in the number of asthma symptom days because of Title IV is about 6 million in the eastern United States; net restricted activity days prevented is about 9 million; and the estimated number of days with acute lower respiratory symptoms prevented, net of restricted activity days, is about 19 million. Together, these represent about 3 percent of the total monetary health benefits.

Estimates of reductions in health effects in Canada are based on estimates of changes in sulfate aerosol concentrations in Canada predicted to result from changes in SO<sub>2</sub> emissions generated in the United States. The estimated benefits for Canada occur primarily in the Windsor-Quebec corridor, where the greatest share of the Canadian population likely to be affected by the transport of SO<sub>2</sub> emissions from the eastern United States is located. The estimates for Canada represent an additional 9 percent of the Title IV benefits in 1997 estimated for the United States population. The estimates for Canada do not increase substantially from 1997 to 2010 presumably because the upwind locations in the United States that affect this area of Canada see their greatest reduction in SO<sub>2</sub> emissions in the first phase of the Title IV program. In 2010, the estimates for Canada add an additional 2 percent to the 2010 estimates for the United States population.

There are many sources of uncertainty and potential error in the mean estimates of health benefits for Title IV reported. Table S-4 shows results of some specific sensitivity analyses conducted to determine the potential effect on results of different assumptions than those selected for the mean estimates. The uncertainty and sensitivity analyses reported here cover only the uncertainties in the concentration-response functions and in the monetary valuation of health effects. Additional uncertainties also exist in the estimates of changes in SO<sub>2</sub> emissions and ambient sulfate concentrations that are used as inputs to the health benefits estimates.

The uncertainty and sensitivity analyses reported here are those that are reasonably amenable to quantitative treatment. It is important to recognize that there are many sources of uncertainty that are not possible to quantify, and that these sensitivity tests are therefore not a comprehensive treatment of all possible sources of uncertainty. What these tests provide, however, is an indication of how the results might change if we found that some of the key default assumptions in the health effects quantification and valuation procedures were inappropriate.

**Table S-4**  
**Sensitivity Analyses Results**

<b>Assumptions</b>	<b>Estimated Annual Health Benefits (billions of 1994 dollars)</b>
<b>United States 1997</b>	
Threshold = 5.0 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$3.1
Threshold = 3.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$6.7
Threshold = 1.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$10.8
Selected SO <sub>4</sub> Health Risks $\times$ 0.4	\$4.8
<b>United States 2010</b>	
Threshold = 5.0 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$15.0
Threshold = 3.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$28.3
Threshold = 1.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$39.3
Selected SO <sub>4</sub> Health Risks $\times$ 0.4	\$18.5
<b>Canada 1997</b>	
Threshold = 5.0 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.0
Threshold = 3.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.0
Threshold = 1.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.7
Selected SO <sub>4</sub> Health Risks $\times$ 0.4	\$0.4
<b>Canada 2010</b>	
Threshold = 5.0 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.0
Threshold = 3.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.0
Threshold = 1.6 $\mu\text{g}/\text{m}^3$ SO <sub>4</sub>	\$0.9
Selected SO <sub>4</sub> Health Risks $\times$ 0.4	\$0.5

Most of the selected concentration-response and monetary value estimates are based on statistically derived results. These estimates therefore have some quantified statistical uncertainty based on the estimated statistical variance in the results. For all of the health effects and monetary value estimates, low and high as well as central estimates were selected based on the estimated statistical variance and analyst judgment. In general, the selected high and low estimates represent plus and minus approximately one statistical standard error.

It is not appropriate to combine all the “low” estimates or all the “high” estimates to calculate upper and lower bounds on the final estimates, because it is highly unlikely that either all the lows or all the highs would be correct. Such extreme assumptions would significantly overstate the statistical uncertainty in the estimates. Instead, we have assigned probability weights to the low, central, and high estimates which when incorporated in the calculation process allow determination of a probability distribution for the total health benefit results.

The results of this procedure are shown in Tables S-2 and S-3 along with the mean estimates for the estimated annual health benefits of Title IV in 2010 for the eastern United States and Canada. All of these estimates are based on the default assumptions, with each estimate representing a different selected point in the estimated probability distribution calculated for the total health benefits. The 20th percentile of the distribution for 2010 in the eastern United States is about \$12 billion in benefits with the default assumptions. This means that 20 percent of the estimated values of benefits are below this amount and 80 percent are above it. The 80th percentile of the distribution is about \$78 billion in benefits with the default assumptions. This means that 20 percent of the estimated values of benefits are above this amount and 80 percent are below it.

Each of the sensitivity tests illustrated in Table S-4 represents estimates of mean annual health benefits in 1994 dollars. Each is calculated in the same way that the default mean was calculated, except for the specified assumption change. A comparison with the default mean therefore illustrates the effect of the change in the assumption. There is considerable uncertainty about whether there is a “safe” level of sulfate aerosol exposure that does not cause any harmful health effects. There is no definitive quantitative evidence that such a threshold exists, but neither is there proof that any amount of sulfate aerosol exposure causes some harmful effect in at least some people. We selected alternative threshold assumptions of  $5.0 \mu\text{g}/\text{m}^3$ ,  $3.6 \mu\text{g}/\text{m}^3$ , and  $1.6 \mu\text{g}/\text{m}^3$  annual median sulfate concentrations to illustrate the potential effects of alternative threshold assumptions on the results of this analysis. The results indicate that with a threshold of  $5.0 \mu\text{g}/\text{m}^3$  annual health benefits are substantially reduced relative to the default mean, falling very close to the 20th percentile default estimate. At thresholds above 5.0 the health benefit estimates would diminish even more. A threshold of  $3.6 \mu\text{g}/\text{m}^3$  results in a mean health benefit estimate that falls about midway between the default mean and the 20 percentile default estimates. At a threshold of 1.6 (or lower), the health benefit estimate is virtually unchanged from the default mean. This illustrates the significance of the threshold question and shows that this continues to be an important research issue from the standpoint of evaluating the health benefits of pollution emission reductions.



There is a possibility that the sulfate-based concentration-response functions may be somewhat upwardly biased because of the typical collinearity between sulfates and other fine particulate constituents in the ambient air. For this sensitivity test we multiply the sulfate based concentration-response functions by 0.4, which is the average ratio between measured sulfates and measured  $PM_{2.5}$  in the eastern United States. This is the maximum adjustment that would be required if the sulfate coefficients represented the total effects of all  $PM_{2.5}$ . This adjustment reduces the annual health benefit estimate in 2010 in the eastern United States to about \$18.5 billion, which is higher than the 20th percentile estimate with the default assumptions. The true sulfate effect is probably between this and the mean default estimate because the sulfate coefficients probably do reflect some, but are unlikely to reflect all, of the effects of other harmful constituents of  $PM_{2.5}$  as well as the effects of sulfates alone.

## **S.4 CONCLUSIONS**

The results of this assessment show that the potential health benefits of reductions in exposures to sulfate aerosols in the eastern United States as a result of the  $SO_2$  emissions reductions required by Title IV are substantial. Based on what we believe is a reasonable interpretation of the available epidemiology and economic evidence on potential health effects of sulfate aerosols and their monetary value, we estimate that the annual health benefits of Title IV required reductions in  $SO_2$  in 2010 in the eastern United States are more likely than not to fall between \$12 billion and \$78 billion, with an estimated mean value of \$40 billion. There is reason to expect some possible upward bias at the higher end of this range, and the results of the sensitivity analyses suggest that there is a good chance that the benefits in 2010 fall between \$12 billion and the estimated mean of \$40 billion. Annual health benefits for eastern Canada resulting from U.S. reductions in  $SO_2$  emissions would add as much as one billion dollars to the U.S. benefit totals in both 1997 and 2010.

We have been careful throughout the report to highlight key assumptions and uncertainties that exist in the quantification procedures used in this assessment, especially in the health effects quantification and valuation portions of the assessment which are the focus of this report. Most of these uncertainties cannot be resolved without substantial new research on several topics.